Cosmic Ray Protons and Magnetic Fields in Clusters of Galaxies and their Cosmological Consequences

Torsten A. Enßlin, Peter L. Biermann
Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

Philipp P. Kronberg
Department of Astronomy, University of Toronto, 60, St. George Street, Toronto, Canada M5S 1A7

and

Xiang-Ping Wu
Beijing Astronomical Observatory, Chinese Academy of Science, Beijing 100080, China

ABSTRACT

The masses of clusters of galaxies estimated by gravitational lensing exceed in many cases the mass estimates based on hydrostatic equilibrium. This may suggest the existence of nonthermal pressure. We ask if radio galaxies can heat and support the cluster gas with injected cosmic ray protons and magnetic field densities, which are permitted by Faraday rotation and gamma ray observations of clusters of galaxies. We conclude that they are powerful enough to do this within a cluster radius of roughly 1 Mpc . If present, nonthermal pressures could lead to a revised estimate of the ratio of baryonic mass to total mass, and the apparent baryonic overdensity in clusters would disappear. In consequence, $\Omega_{\rm cold}$, the clumping part of the cosmological density Ω_o, would be larger than $0.4\, h_{50}^{-1/2}$.

Subject headings: cosmic rays — cosmology: observations — dark matter — galaxies: clusters: general — intergalactic medium — magnetic fields

1. Introduction

Clusters of galaxies, being the most massive coherent objects in the universe, are important probes of the cosmological density. X-ray observations allow a measurement of the density profile of the hot intracluster gas, which dominates the visible, baryonic mass $M_{\rm b}$ of a cluster. Estimates of the total mass $M_{\rm tot}$ can be made from a virial analysis of the galaxy velocities, by integration of the hydrostatic equilibrium between gravitational forces and thermal pressure, or by analyzing background objects that are gravitationally lensed by the cluster. Calibrating $\Omega_{\rm b}$ from the standard Big Bang nucleosynthesis with the value $\Omega_{\rm b}/\Omega_{\rm cold} \approx M_{\rm b}/M_{\rm tot}$ given by clusters should give then a lower limit to Ω_o, if $\Omega_{\rm cold}$ is the part of the matter which clumps on the scale of clusters. Unfortunately, the mass derived from velocity dispersion and from hydrostatic equilibrium appears to be often much lower than the mass derived by lensing methods.

Miralda-Escudé & Babul (1995) derived the mass of Abell 2218 and Abell 1689 from gravitationally lensed arcs and from X-ray observations and found a mass shortfall of a factor 2.5 ± 0.5. Similar work done by Wu (1994) gave a factor of $3-6$ within a central radius of 300 kpc h_{50}^{-1} for four different clusters. Even in the rich, early cluster RXJ1347.5-1145 at $z = 0.451$ a mass discrepancy of a factor $2-3$ is reported by Schindler et al. (1996). Conversely, Squires et al. (1995) have re-examined Abell 2218 with HST images and found accordance between the different mass determinations at a radius of 800 h_{50}^{-1} kpc, applying a weak lensing method that reconstructs the mass distribution by using the distortion of background galaxies. However, they note that their lensing mass could be too low, since it depends on assumptions about the

mass distribution outside the image radius. But if their mass values are correct, then the mass discrepancy would be largely removed for regions far outside the core. Allen, Fabian, & Kneib (1995) show for the cluster PKS0745 that a two-temperature model of the gas, consistent with a strong cooling flow, has no discrepancy between the hydrostatic mass and an arc-determined mass at a small radius of $46\,h_{50}^{-1}$ kpc. D.-W. Kim & Fabbiano (1995) find a discrepancy between masses estimated from X-rays and the virial masses from the velocity dispersions of the galaxies in the NGC 507 group. But while many measurements give virial masses as low as the X-ray masses (Bahcall & Lubin 1993) , these virial mass estimates could be a strong underestimate of the total masses of clusters, predicted from the appearance of dynamical friction in simulations of the galaxy and dark matter content of clusters (Serna, Alimi, & Scholl 1994; Carlberg 1994a) . This would be consistent with a number of observations of velocity and luminosity segregation of galaxies in clusters (Yeppes, Domínguez-Tenreiro, & Del Pozo-Sanz 1991; Biviano et al. 1992; Buote & Canizares 1992; Carlberg 1994b; Loveday et al. 1995) . The masses of clusters are overestimated if the measured velocity dispersion is seriously affected by infalling galaxies. But a parameter-free examination of the Coma cluster with 1500 galaxy positions and 450 measured velocities by Merritt & Gebhardt (1996) shows that, even in this case with solid statistics, the total mass of the cluster is poorly defined and could be several times the value derived by assuming that mass follows light. The average trend of a large sample of clusters show a clear signal for a strong mass discrepancy between lensing and hydrostatic masses, which extends up to a radius of 1 Mpc (Wu & Fang 1996).

Several possibilities have been suggested to resolve the mass discrepancy between X-ray and lensing masses, including a projection effect of an asymmetrical matter distribution (for a discussion see Miralda-Escudé & Babul 1995) . Additionally, substructuring can cause significant uncertainties in the computation of the dynamical cluster mass. Loeb & Mao (1994) and Steigman & Felten (1995) explained the mass discrepancy as due to ignorance of nonthermal pressure in the hydrostatic equilibrium of the intracluster medium (ICM).

In this paper we want to focus on the role that the nonthermal cosmic ray pressure could play in supporting the intracluster ionized gas. In the disk of our Galaxy cosmic rays (CR) are trapped in the galactic magnetic field, which is frozen into the interstellar gas through its ionized component. Recent evidence that the ICM of galaxy clusters is permeated by significant magnetic fields suggests that a similar trapping of CR by the ICM field occurs, although direct measurement of the ICM cosmic ray component is more difficult to make. For our galaxy, the effects of the cosmic ray gas component are reasonably well understood — *cf.* Parker's (1969) review article . If the pressure of these nonthermal phases exceeds the thermal pressure by a factor of order unity, instabilities will grow, and convective processes will result. This sets a maximum level at which nonthermal constituents will likely be present. If there are a sufficient number of powerful sources for these pressures, then the nonthermal pressures should approach roughly this limiting value — which we can also consider as a *maximum* value. Since we might expect a constant factor between thermal and CR-pressure, we parametrize the CR-energy density as a fraction of the thermal energy

$$\varepsilon_{\rm CR}(r) = \alpha_{\rm CR}\,\varepsilon_{\rm th}(r)\,. \qquad (1)$$

For our Galaxy, Parker showed that a magnetic plus cosmic ray pressure of 1.5 times the thermal pressure results from the following measurements and basic physical considerations:

(a) Direct observation of the cosmic ray spectrum in the solar neighborhood, combined with observation of Faraday rotation, which quantitatively establishes both cosmic ray and magnetic pressure component in the interstellar medium.

(b) Hydrostatic effects, which determine the (observable) scale height of the gas distribution in our galaxy, which is sensitive to gravity and pressure.

(c) A theoretical limit to the gas height scale, given by pressure limiting instabilities for magnetic fields perpendicular to the gravitational forces in a disk filled with a cosmic ray gas.

A key aim of this paper is to adapt our most recent knowledge of the multi-phase galactic disk gas to the intracluster medium of galaxy clusters. By analogy to the interstellar medium, we propose that the ICM is kept somewhere close to a "stability limit" by sources of cosmic rays and magnetic fields. Whereas the cosmic ray component of the ICM comes from supernova remnants, we propose that radio galaxies are the corresponding CR sources in galaxy clusters. We note the detailed analogy to the interstellar medium: Supernova remnants provide the interstellar medium with CRs and high velocity motion in a phase of their evolution *after* they are clearly discernible as radio and/or X-ray sources. Similary, we expect radio galaxies to distribute most of their cosmic rays, magnetic fields and high velocity motion in an evolutionary phase *after* they are recognizable in the radio. Thus, we require a basis for assuming that there are sufficient CR sources to affect the nonthermal pressure component in the ICM. Although the field topology in clusters is not yet well understood, we can estimate the pressure-determining factor by using approach (b) to get a rough estimate.

We investigate the question of a new pressure component in clusters due to cosmic rays from three different lines of investigation and argument.

(i) We will argue from current and recent observations that magnetic fields and energetic protons provide a substantial internal energy component in clusters of galaxies. Further, there is hope that these CR protons should be detectable in the near future, if they are indeed present. The main component of cosmic rays and magnetic fields in the ICM should come from radio galaxies (RG), which are frequently found in the central regions of clusters. Over the lifetime of galaxy clusters, radio galaxies should have injected fields and energetic particles, whose combined energy is at least equal to the present-epoch thermal energy content of the central region. To demonstrate this, we calculate the energy output from clusters by X-ray cooling and their thermal energy-content. We compare these numbers with the jet power-input from radio galaxies into the ICM at the present cluster epoch, and integrated over the clusters' history. We do this global calculation for clusters and radio galaxies by integrating, separately, their X-ray- and radio-luminosity functions, and by using statistical correlations between properties and luminosities of these objects.

(ii) Nonthermal pressure should show up in a comparison of gravity forces and thermal pressure gradients. The latter are used in deriving hydrostatic masses of clusters, and it is these masses which are lower by a factor of typically 3 than masses derived by gravitational lensing. The missing pressure component that is required to "close" the discrepancy is approximately 2 times the thermal pressure.

(iii) Due to the expected complicated field topology and local variations of field strength, a universal, stable and time-independent configuration of fields, cosmic-rays and thermal gas is unlikely. However, turbulent transport of magnetic fields and cosmic rays over large distances in a cluster should permit a factor between nonthermal and thermal pressure that is comparable to the one in our (much smaller) galactic disk.

In the following sections we present arguments to show that, under reasonable assumptions, the energy output from radio galaxies *can* provide energy in the required order of magnitude to close the gap between hydrostatic and direct gravitational estimates of masses at least in the central regions of galaxy clusters. Throughout this paper we adopt $H_o = 50\,h_{50}$ km s^{-1} Mpc^{-1} and $q_o = 0.5$. The term cosmic rays (CRs) will primarily stand for energetic protons.

2. The energy content of the ICM

2.1. The thermal energy

The cosmological density of the X-ray luminosity of galaxy clusters can be calculated by an integration of the X-ray luminosity function of clusters of galaxies, proposed by Edge et al. (1990) in the 2 – 10 keV band

$$\frac{dN}{dL_{X,2-10}} = A L_{X,2-10}^{-\alpha} \exp(-L_{X,2-10}/L_o)\,\mathrm{Mpc}^{-3}, \tag{2}$$

where the luminosity $L_{X,2-10}$ is given in units of $10^{44}\,\mathrm{erg\,s^{-1}}$ and $A = 10^{-6.57\pm0.12}$, $\alpha = 1.65 \pm 0.26$ and $L_o = 11^{+0.4}_{-0.2}$ ($cl = 90\%$ within this section). We can use the strong correlation $L_X = 10^{B_{\rm bol}}\, L_{X,2-10}^{A_{\rm bol}}$ ($A_{\rm bol} = 0.94 \pm 0.03, B_{\rm bol} = 3.02 \pm 0.15$ and the luminosities in $\mathrm{erg\,s^{-1}}$) (Edge & Steward 1991) to obtain an estimate of the bolometric luminosity of clusters. Integrating from the lower limit $10^{43}\,\mathrm{erg\,s^{-1}}$ to infinity gives $L_X \approx 2 \cdot 10^{40}\, h_{50}$ W Gpc^{-3}. In order to estimate the thermal energy content we use a β-model for the cluster gas

$$n_{\rm e}(r) = n_o\, \left(1 + (r/r_{\rm core})^2\right)^{-3/2\beta} \tag{3}$$

and the cooling function for thermal bremsstrahlung

$$\Lambda_X(T) = \Lambda_o\, n_{\rm e}^2\, (k_B T)^{1/2}\,, \tag{4}$$

where $n_{\rm e}$ is the electron density, T the temperature and $\Lambda_o = 5.96 \cdot 10^{-24}\mathrm{erg\,s^{-1}\,cm^3\,keV^{-1/2}}$. An integration of the luminosity to the largest observed radius, $r_{\rm obs} \approx 10\, r_{\rm core}$, gives

$$L_X = \Lambda_o\, n_o^2\, (k_B T)^{1/2}\, r_{\rm core}^3\, f(r_{\rm obs}/r_{core}, 3\beta)\,, \tag{5}$$

where

$$f(x,\gamma) = 4\pi \int_0^x dy\, \frac{y^2}{(1+y^2)^\gamma} = 2\pi\, B_{\frac{x^2}{1+x^2}}(\frac{3}{2}, \gamma - \frac{3}{2}) \tag{6}$$

depends only on the geometry. B is the incomplete Beta function. The thermal energy content $(3\, n\, k_B\, T)$ integrated out to a radius r yields, with equation (5),

$$E_{\rm th}(r) = 3\,(k_B T)^{3/4}\, L_{X,bol}^{1/2}\, r_{\rm core}^{3/2}\, \frac{f(r/r_{\rm core}, 3\beta/2)}{\sqrt{f(r_{\rm obs}/r_{\rm core}, 3\beta)}}. \tag{7}$$

Using the good correlation $k_B T = 10^{B_{\rm T}} L_{X,2-10}^{A_{\rm T}}$ ($A_{\rm T} = 0.28 \pm 0.05, B_{\rm T} = -11.73 \pm 0.20, k_B T$ in keV and $L_{X,2-10}$ in $\mathrm{erg\,s^{-1}}$) (Edge & Steward 1991) we can translate temperature into luminosity with good reliability. Given that the correlation of $r_{\rm core}$ with T is weak, we assume a constant characteristic core radius of $r_{\rm core} = 250\, h_{50}^{-1}$ kpc and $\beta = 0.6$ for all clusters. Integration of the luminosity function (2) gives an averaged thermal energy of the ICM within the cooling radius $r_{\rm cool} \approx 1.5\, r_{\rm core}$ which is $E_{\rm th}(r_{\rm cool}) \approx 3 \cdot 10^{57}\, h_{50}^{1/2}$ J Gpc^{-3}. This number is nearly independent of β within the range 0.6 ... 1.0 and of $r_{\rm obs}$ as long as it is several times $r_{\rm core}$. The thermal energy within $1.5\,\mathrm{Mpc}\, h_{50}^{-1}$ depends even more on β and is one order of magnitude higher. Shifting β to 1.0 would lower the thermal energy content within $1.5\,\mathrm{Mpc}\, h_{50}^{-1}$ by 40%.

2.2. Recent determinations of intracluster field strengths

Statistical evidence for widespread intracluster magnetic fields comes from a combination of Faraday rotation measurements, combined with X-ray determined electron densities in the same ICM gas which produces the Faraday rotation. The most recent analysis, by K.-T. Kim, Tribble, & Kronberg (1991) for a sample of 50 Abell clusters, indicates a typical ICM field strength of $\sim 2\mu\mathrm{G}(l_{\rm frs}/10\,\mathrm{kpc})^{-1/2} h_{50}^{-1/2}$ (where

$l_{\rm frs}$ is the typical field reversal scale). This estimate, as (Kim et al. 1991) argue, is likely to increase, especially in the cores, due to various uncertain factors such as smaller turbulence scales (*cf.* Feretti et al. 1995) , and the fact that their average result (which used background radio sources) is weighted toward sightlines outside of the cluster core region where the field strength is likely weaker.

It is interesting to note that, in some clusters, high field values have been measured, and approximate equality between magnetic and thermal pressure has been established (*cf.* Taylor and Perley 1993). These observations, of differential "Faraday screen" effects over extended radio lobes of powerful radio galaxies inside of clusters, reveal intracluster field strengths of order $30\mu{\rm G}\, h_{50}^{-1/2}$, *e.g.* in the core of the Hydra cluster (David et al. 1990) . A similar result was obtained for the host cluster of Cygnus A (Taylor & Perley 1993) . It may not be a coincidence that the clusters with powerful radiogalaxies also contain a cooling flow (Christodoulou & Sarazin 1996).

The recent trend of results for, *e.g.*, the Coma cluster is that smaller field reversal scales have emerged as the resolution of the Faraday RM images of cluster head-tail sources has improved. This causes estimates of core ICM field strengths to increase correspondingly (*cf.* Felten (1996) for a detailed discussion on this point). Thus, the reversal scales established by new, higher resolution images of the extended head-tail source in the Coma Cluster give cluster core ICM field strengths of 5 μG or higher (Feretti et al. 1995).

Recent Faraday rotation data suggest that the general cluster population (as distinct from clusters presently known to have cooling flows) are able to produce fields in their core regions (by whatever mechanism) of up to $10\mu{\rm G}\, h_{50}^{-1/2}$ or more. This is consistent with the trend of recent attempts to measure cluster ICM magnetic field strengths (Kim it et al. 1990, Kim it et al. 1991, Feretti *et al.* 1995).

If the turbulence scale, $l_{\rm frs}$, is as small as ~ 0.1 kpc, then the sightline-averaged magnetic field would as much as $\sim 20\,\mu{\rm G}\, h_{50}^{-1/2}$. The resulting magnetic pressure would, at that level, be of the order of the thermal pressure. Since the strength of the fields and the typical field scale depend on the field reversal scale, $l_{\rm frs}$ is kept in all formulae as a free parameter – this allows to use them in the case of weak ($l_{\rm frs} \approx 10$ kpc) and strong ($l_{\rm frs} \approx 0.1$ kpc) magnetic fields.

Field values of this order support our notion of an additional non-thermal pressure component in cluster cores, although they need not be precisely in energy equipartition with the CR protons. It is also relevant to note that they are also comparable with (independently estimated) equipartition field values in weak relics of "old" extended extragalactic radio sources (*cf.* Kronberg 1994) which are near $10\, h_{50}^{2/7}\, \mu$G (Miley 1980) .

But there is no evidence as yet for or against dynamically important fields outside of cluster core regions.

2.3. The gamma-ray emission and intracluster cosmic ray densities

Dar & Shaviv (1995) proposed to explain the diffuse extragalactic gamma ray spectrum, and predict detectable gamma ray fluxes from the nearest clusters. They assume that the cosmic ray density in galaxy clusters is similar to that in our own galaxy and that the density has no radial dependence. We use a more realistic model, in which the cosmic ray energy $\varepsilon_{\rm CR}$ density scales with the thermal energy density of the gas:

$$\varepsilon_{\rm CR}(r) = 3\, n_{\rm e}(r)\, k_B T\, \alpha_{\rm CR} \qquad (8)$$

where $\alpha_{\rm CR}$ is the scaling ratio between the thermal and CR energy densities defined in equation (1). We now estimate the production rate for gamma rays above 100 MeV by π_o-decay after hadronic interactions

of the energetic protons with the background gas. This is given by

$$\frac{dn_\gamma(>100\mathrm{MeV})}{dt} = q_\gamma\, \varepsilon_{\rm CR}\, n_{\rm target} = 3\, q_\gamma\, n_{\rm e}^2\, k_B T\, \alpha_{\rm CR} \tag{9}$$

where $n_{\rm target}$ is the proton density, and the parameter $q_\gamma = 0.39 \cdot 10^{-13}\mathrm{cm}^3\,\mathrm{erg}^{-1}\,\mathrm{s}^{-1}$ applies to a proton spectrum similar in slope to that observed in our galaxy (*cf.* Drury, Aharonian, & Völk 1994) . We compare equation (9) with the rate of thermal bremsstrahlung (equation (4)) to obtain a ratio for the observed fluxes gamma-rays $F_\gamma(>100\mathrm{MeV})$ and X-rays F_X for galaxy clusters

$$\frac{F_\gamma(>100\mathrm{MeV})}{F_X/\mathrm{erg}} = 32 \left(\frac{k_B T}{\mathrm{keV}}\right)^{1/2} \alpha_{\rm CR}\,. \tag{10}$$

We note that this ratio is practically independent of the assumed cosmology. Taking temperatures and X-ray fluxes from David et al. (1993) and assuming $\alpha_{\rm CR} = 1$, we list in table 1 our calculation of the expected gamma-ray fluxes for some of the brightest clusters along with fluxes calculated by Dar & Shaviv (1996) . The discrepancy between our fluxes and theirs are due to the different CR-density profiles. We note, that if the the CRs have a steeper radial density profile than the gas – reasonable due to the mostly central injection and due to a decreasing mass discrepancy with radius – our gamma ray fluxes have to be reduced.

If there is an anticorrelation between the presence of cooling flows and cosmic ray protons due to the possibility of a slowing down of the cooling instability by nonthermal pressure, then our calculated values for Perseus and Ophiuchus could be too high, since these have strong cooling flows.

The above fluxes are close to the detection limit of EGRET, which suggests that the unknown factor $\alpha_{\rm CR}$ between the CR-and the thermal energy density in these clusters could be determined in the near future for some clusters. For the Coma and Virgo clusters upper limits from EGRET measurements are now available and given in table 1. In the case of Coma, the upper limit restricts the unknown parameter $\alpha_{\rm CR}$ to be lower than 2/3 or the CRs are in equipartition only within the central region. Unfortunately the expected fluxes above some TeV are orders of magnitude too low to be detectable by the HEGRA or other airshower experiments.

3. Injection of nonthermal pressures in clusters of galaxies by radio galaxies

3.1. The jet power of radio galaxies

Recent analysis of airshower data by Stanev et al. (1995) and Hayashida et al. (1996) suggests a correlation between the arrival directions of the highest energetic events of observed cosmic rays and the supergalactic plane. This is consistent with earlier arguments (Biermann & Strittmatter 1987; Rachen & Biermann 1993; Rachen, Stanev, & Biermann 1993) that radio galaxies (RG) are sources of high energy cosmic rays. Of interest for our present purposes is that these new observations imply the production of very energetic relativistic protons, besides relativistic electrons, in the lobes of radio galaxies. In order to explain the cosmic rays at energies beyond $3 \cdot 10^{18}\,\mathrm{eV}$ observed at Earth, we need to assume a high proton energy density within lobes of radio galaxies. This requires that the power of the jet to be up to an order of magnitude higher than the value which follows from minimal energy arguments assuming no protons (Rachen & Biermann 1993) . A factor $f_{\rm power}$ higher than 1 between real jet power and the minimal possible jet power consistent with radio observations can also be expected when we consider possible acceleration mechanisms for protons, which can be very effective (Bell 1978a, 1978b) . The recent gamma ray detection of Mkn 421 (Petry et. al. 1996) has a natural explanation by hadronic interactions, which implies that high energy protons are indeed present within the jet-lobe system of RGs (Halzen 1996). We use here

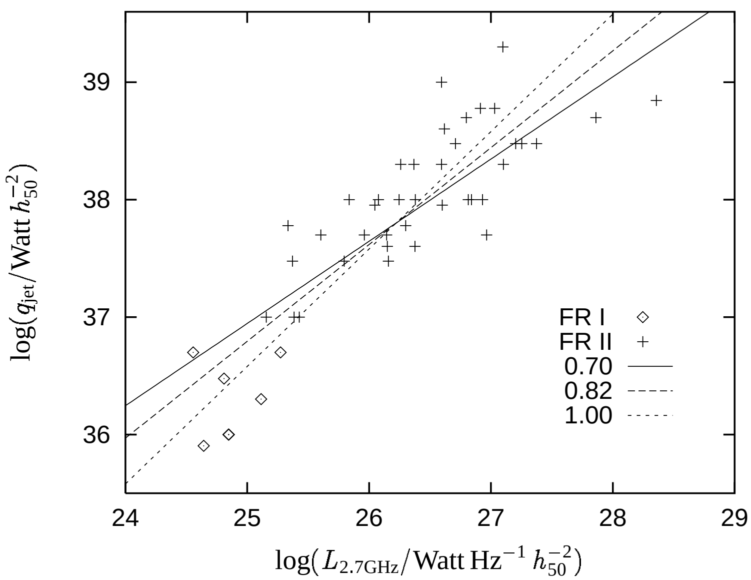

Fig. 1.— Jet power of radio galaxies $\log(q_{\rm jet}/{\rm Watt}\,h_{50}^{-2})$ from (Rawlings & Saunders 1991) over their radio luminosity $\log(L_{\rm 2.7GHz}/{\rm Watt\,Hz^{-1}}\,h_{50}^{-2})$ from (Laing, Riley & Longair 1983) . The power laws discussed in the text $q_{\rm jet} \sim L_{\rm 2.7GHz}^{b}$ are shown. Protons are assumed in the jet corresponding to $f_{\rm power} = 3$.

a conservative factor of $f_{\rm power} = 3$. At this point we link our argument for the importance of relativistic proton energies to previous analyses of the energetics of extragalactic radio source jets and lobes: In an interesting analysis, Rawlings & Saunders (1991) evaluated the jet power of a sample of radio galaxies. Beginning with the observed synchrotron emission of the lobes Rawlings & Saunders (1991) calculated the minimum necessary power in relativistic electrons and magnetic fields which the jets must inject into the radio lobes in order to produce the observed radio emission. Since this calculation omitted the energy contribution of the relativistic protons, we have increased these estimates of the total jet power by $f_{\rm power} = 3$ times the value given by Rawlings & Saunders (1991). As indicated above, we feel that a factor of 3 here is conservative. In a related investigation, Donea & Biermann (1996) have analysed recent AGN UV spectra in terms of a sub-Eddington accretion disk which drives the innermost parts of a radio galaxy jet. If this model is correct, then not only relativistic protons but also a kinetic energy component of the thermal gas exists $--$ which would drive $f_{\rm power}$ even higher. Fig. 1 shows a double-logarithmic plot of the jet power data $q_{\rm jet}$ (assuming $f_{\rm power} = 3$) against $L_{\rm 2.7GHz}$, the total radio luminosity at 2.7 GHz, derived from Laing, Riley, & Longair (1983) . The relation is

$$q_{\rm jet} = 10^{a} L_{\rm 2.7GHz}^{b} \tag{11}$$

for which $b = 0.82 \pm 0.07$, $a = 38.28 \pm 0.18 - 26.22 \cdot b$ ($cl = 68\%$), $q_{\rm jet}$ in Watt h_{50}^{-2} and $L_{\rm 2.7GHz}$ in Watt ${\rm Hz}^{-1}\,h_{50}^{-2}$. This is consistent with the relation derived by Falcke & Biermann (1995) and Falcke, Malkan, & Biermann (1995) which demonstrates that the radio luminosity and jet power can be connected by a simple power law through the entire spectrum of RG $--$ from the weaker, more center-brightened FR I to the more powerful, edge-brightened FR II galaxies. The same relation, which yields $b = 0.7$, has also been successfully tested down to the scale of stellar jets and luminosities (Falcke & Biermann 1996) .

3.2. The intracluster medium energy input from radio galaxies

There is evidence for strong interaction between radio galaxies and the ICM, since hot, compressed and very X-ray luminous regions are observed within 20-200 kpc h_{50}^{-1} from the radio galaxies in clusters (Jones & Forman 1984; Böhringer et al. 1993; Burns et al. 1994; Sarazin, Baum & O'Dea 1995) . In this section, we appeal to various statistical analyses which can be used to estimate the likely extragalactic jet energy input into the ICM over a relevant period of cosmic time. We note, that ICM refers to the thermal gas, the magnetic fields and the CRs and therefore energy input includes heating of the gas, but also injection of CRs and fields. The radio luminosity function (RLF) of entire clusters compared to that of radio galaxies indicates that the fraction of the radio galaxies which lie in clusters can be reasonably estimated to be $f_{\rm cluster} \approx 0.3...0.5$ (Owen 1975; Gubanov & Dagkesamanskii 1988). On a cosmic scale, radio galaxies are significantly more clustered than galaxies in general, or even elliptical galaxies (Bahcall & Chokshi 1992) , and the bivariate luminosity function (optical & radio) of ellipticals inside and outside of clusters has been found to be roughly the same, independent of cluster richness class and RG radio power (Auriemma et al. 1977; Ledlow & Owen 1995). In other words, the probability that a potential progenitor of a jet-lobe radio galaxy will actually produce one is not affected by the galaxy's membership in a cluster. An additional, approximate scaling argument can be made as follows: Cluster cores contribute ≈ 10 % of the light in the universe (Salpeter 1984) , and radio galaxies in rich clusters, especially the powerful ones, occur preferentially near the center (Ledlow & Owen 1995). Given the information on the similarity of the bivariant luminosity function inside and outside of clusters, it could be supposed that the cores of clusters contain 10 % of all radio galaxies and therefore absorb some fraction $f_{\rm core}$ of the total jet power. We therfore estimatete $f_{\rm core} \approx 0.1$. The corresponding fraction $f_{\rm cluster}$ absorbed by all clusters is $f_{\rm cluster} \approx 0.3...0.5$.

In an attempt to arrive at some statistical estimate of the jet power output of RG we have integrated the *evolving* part of the RLF given in equation (7) in (Dunlop & Peacock 1990) . Because of the sample chosen by Rawlings & Saunders (1991) our $q_{\rm jet}$-$L_{2.7\rm GHz}$ correlation is assuredly valid above $10^{24.5}\,h_{50}^{-2}{\rm W\,Hz}^{-1}$, but it must be extrapolated to lower luminosities. To accommodate uncertainties in this extrapolation, we calculated the total jet power output, $Q_{\rm jet}(z)$, using three different power law indices, $b = 0.7, 0.82$ and 1.0 respectively. The expression for $Q_{\rm jet}$ is

$$Q_{\rm jet}(z) = \int \frac{dN(L_{2.7\rm GHz}, z)}{dL_{2.7\rm GHz}}\, q_{\rm jet}(L_{2.7\rm GHz})\, dL_{2.7\rm GHz} \tag{12}$$

A numerical integration of the jet power-luminosity correlation gives the average jet power delivered per cosmological comoving volume $Q_{\rm jet}(z = 0) = 11, 4, 2 \cdot 10^{40}\,{\rm Watt\,Gpc}^{-3}\,h_{50}^{-2}$, corresponding to the three power law slopes mentioned above; $b = 0.70, 0.82, 1.00$ These are shown in fig. 1. The energy input into the central region of clusters from RG is the fraction $f_{\rm core}\,Q_{\rm jet}(z = 0)$, which is $0.4 \cdot 10^{40}\,{\rm Watt\,Gpc}^{-3}\,h_{50}^{-2}$ for $b = 0.82$. This is half an order of magnitude lower than the central X-ray luminosity of clusters, about $10^{40}\,{\rm Watt\,Gpc}^{-3}\,h_{50}$ which is, in turn, roughly 2/3 of the total luminosity for our β-model-parameters $r_{\rm cool} = 1.5\,r_{\rm core}$ and $\beta = 0.6$.

3.3. Cooling of the cosmic ray protons vs accumulation

In order to decide if the injected jet power dissipates and heats the gas, or alternativly, accumulates and supports the ICM we must estimate the time scale of the dissipation processes. The dissipation of magnetic fields is very difficult to quantify, but the CR part of the outflow of radio galaxies could be affectedby numerous processes. The relativistic electrons lose their energy relatively quickly through synchrotron emission in the cluster magnetic fields and Compton scattering with photons of the microwave background. This contrasts with the energetic protons, whose Compton and synchrotron cooling times are much longer than the Hubble-time. The energy loss of a proton with energy $\varepsilon = \gamma_{\rm p}\, m_{\rm p} c^2$ by electronic excitations in a

plasma is given by Gould (1972) :

$$-\left(\frac{d\gamma_{\rm p}}{dt}\right)_{\rm ee} = \frac{4\,\pi\,e^4\,n_{\rm e}}{m_{\rm e}\,c^3\,m_{\rm p}\,\beta_{\rm p}}\left[\ln\left(\frac{2\gamma_{\rm p} m_{\rm e} c^2 \beta_{\rm p}^2}{\hbar\omega_{\rm pl}}\right) - \frac{\beta_{\rm p}^2}{2}\right] \tag{13}$$

Here, $\beta_{\rm p}\,c$ is the velocity of the proton and $\omega_{\rm pl} = \sqrt{4\pi e^2 n_{\rm e}/m_{\rm e}}$ the plasma frequency. Inserting a typical density of $n_{\rm e} = 10^{-3}\,{\rm cm}^{-3}$ gives a cooling time

$$t_{\rm ee} = \left[-\frac{1}{\gamma_{\rm p}}\left(\frac{d\gamma_{\rm p}}{dt}\right)_{\rm ee}\right]^{-1} = 4.7\cdot 10^{10}\,\beta_{\rm p}\,\gamma_{\rm p}\,\left[1+\frac{\ln(\beta_{\rm p}^2\,\gamma_{\rm p}) - \beta_{\rm p}^2/2}{41}\right]^{-1}\ {\rm yrs} \tag{14}$$

which is longer than a Hubble-time for $\beta_{\rm p} > 0.4$. Cosmic rays streaming along a magnetic field are cooled by excitation of Alfvén waves (Wentzel 1974) , which changes their momenta $\beta_{\rm p}\gamma_{\rm p}m_{\rm p}$

$$-\left(\frac{d\beta_{\rm p}\gamma_{\rm p}}{dt}\right)_{\rm A} = \frac{V_{\rm A}}{L}\,\beta_{\rm p}\gamma_{\rm p} \tag{15}$$

where $V_{\rm A} = B/\sqrt{4\,\pi\,m_{\rm p}\,n_{\rm e}}$ is the speed of the waves and L is the scale height of the CR distribution measured following the magnetic field. Rephaeli (1987) equates this length to the core radius $r_{\rm core}$ of the cluster since the radial scale height of the gas and the CR should be similar. But $L = r_{\rm core}$ is correct only in the case of radial magnetic fields in clusters, since then the CR can move straight radially, and the length of a CR path is equal to the Euclidean distance between starting and final point of the path. In the more realistic case of tangled magnetic fields the path length L must be measured following the field lines, which maintain the path for the CRs in order to arrive at a position one core radius in radial distance from their starting point. This path-length must be of the order $r_{core}^2/l_{\rm frs}$ due to the random walk of the field line through the ICM, with a step size given by the field reversal scale $l_{\rm frs}$. But the Euclidean scale height of the CRs distribution, giving the pressure gradient which goes into the hydrostatic equation, is still one core radius. Magnetic fields are typically $B \approx 2\,\mu G(l_{\rm frs}/10{\rm kpc})^{-1/2}$, and a typical core radius is $r_{\rm core} = 250$ kpc. We get a cooling time

$$t_{\rm A} = \frac{L}{V_{\rm A}} = 4.4\cdot 10^{10}\,\left(\frac{l_{\rm frs}}{10{\rm kpc}}\right)^{-1/2}\,\left(\frac{n_{\rm e}}{10^{-3}\,{\rm cm}^{-3}}\right)^{1/2}\ {\rm yrs} \tag{16}$$

and of course a larger time if $l_{\rm frs} < 10$ kpc. The time scale for energy loss by proton-proton interaction is of the order (or even larger) of the average time between collisions of the CR protons with the gas

$$t_{\rm pp} = (\sigma_{\rm pp}\,n_{\rm e}\,\beta_{\rm p}\,c)^{-1} = 3.5\cdot 10^{10}\,\beta_{\rm p}^{-1}\,\left(\frac{n_{\rm e}}{10^{-3}\,{\rm cm}^{-3}}\right)^{-1}\ {\rm yrs}\,. \tag{17}$$

There might be some adiabatic cooling of the CRs when they and their enclosing magnetic fields ascend in the gravitational field of the cluster. But the energy lost by the energetic particles is gained by the magnetic fields and the thermal component of the ICM, and it returns to the particles if the same plasma is dragged down by infalling matter. Since clusters are still growing, Völk, Aharonian & Breitschwerdt (1996) concluded that there should be a sizeable adiabatic increase in the CR energy content of the ICM.

Thus, the cooling of energetic protons is small, and may even be compensated for by additional CR sources such as supernovae, accretion shocks, in-situ acceleration and adiabatic compression. Further, even the electrons can to some extent be re-accelerated by energy redistribution in the ICM, as Kim et al. (1991) have suggested to explain the spectral index of the Coma cluster's radio halo.

The number $f_{\rm power}$ depends on the ratio $k_{\rm p} = \varepsilon_{\rm p}/\varepsilon_{\rm e}$ between baryonic and electronic energy density within the radio lobes of radio galaxies. (In the case of a lobe field energy density higher than the microwave

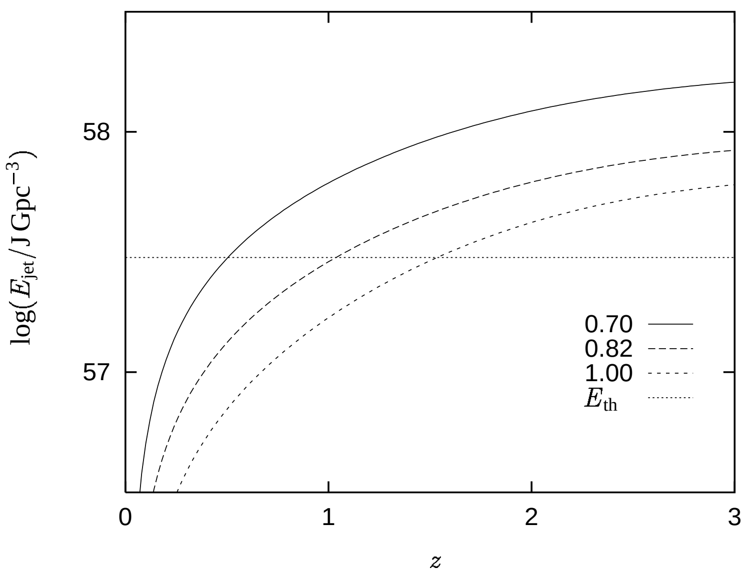

Fig. 2.— The time-integrated cosmological jet power $\log(E_{\rm jet}/{\rm J\,Gpc^{-3}})$ which is injected into the cores of cluster is shown as a function of the redshift z, which gives the time of the lower end of the integration by equation (18). The thermal Energy of the ICM in the cluster cores $E_{\rm th}$ is shown. ($f_{\rm power} = 3$ and $f_{\rm core} = 0.1$).

energy density: $f_{\rm power} = 1 + k_{\rm p}$). If one follows the radio emitting medium which leaves the lobes and diffuses into the cluster medium, this ratio increases strongly, because the electrons suffer from numerous cooling mechanisms, where the protons nearly keep their energy. This cooling of the electrons is clearly visible in the steepening of the spectral index of radio emission close to radio galaxies in clusters (e.g. Sarazin, Baum & O'Dea 1995). Therefore a very high k_p within the cluster medium is reasonable, indeed necessary if one assumes the magnetic fields and CR energy density values that we do.

3.4. Evolutionary effects of cosmological jet power

Since the RLF is a strongly evolving function of the redshift z, the energy input by RG must have been much stronger in the past. This is of interest to calculate, since earlier jet input power might have been *accumulated* in the thermal gas, cosmic rays, and magnetic phase of the ICM. Given a thermal energy content of the ICM within the cooling, central region which is $E_{\rm th}(r_{\rm cool}) \approx 3 \cdot 10^{57}\, h_{50}^{1/2}$ J Gpc^{-3} and $E_{\rm th}(1.5\,{\rm Mpc}) \approx 3 \cdot 10^{58}\, h_{50}^{1/2}$ J Gpc^{-3} then, as we have argued, the total accumulated energy content should be of the order of $10^{58}\, h_{50}^{1/2}$ J Gpc^{-3} within the central region, after allowing for cosmic rays and magnetic fields.

Evidence has been found for evolution of the cluster luminosity function: Edge et al. (1990) find that higher redshift high-luminosity clusters are under-represented in their sample, which fact they take to indicate strong evolution at recent epochs. Castander et al. (1995) confirm this observation, and conclude that non-gravitational heating may be important in the evolution of clusters. Further, a strong evolution of the luminosity function in the Einstein 0.3 - 3.5keV band has been found over the redshift range $z = 0.17$ to $z = 0.33$ (Henry et al. 1992) which is consistent with a lower ICM temperature at higher redshift. This leads to the important consequence that the high present day X-ray cooling of clusters cannot be extrapolated to the past.

In fig. 2 we plot the accumulated jet power that was injected into the cores of clusters (assuming $f_{\rm core} = 0.1$) in the interval since some past time (related to the redshift z) and the present, using the standard expression for time in an Einstein-de Sitter cosmology

$$t(z) = \frac{2}{3\,H_o}\,\left[1 - (1+z)^{-3/2}\right]. \tag{18}$$

We do not take adiabatic cooling due to the Hubble-expansion into account because we are interested in the deposition of energy in cluster cores, which are largely decoupled from the Hubble flow. With the above parameters of the β-model and of the efficiency of injection of nonthermal energies ($f_{\rm power}$ & $f_{\rm core}$) we find that the thermal energy $E_{\rm th}$ of the ICM could have been *accumulated* in less than a Hubble-time. The above mentioned total energy content of $3\,E_{\rm th}$, could amount to a virtual replacement of the thermal energy of the cooling region ICM by radio galaxies and their "fossils", given the conservative level of our relativistic proton energy component. At larger radii, the ratio of nonthermal to thermal pressure should decrease, because the thermal energy content is one order of magnitude higher within 1.5 Mpc than within $r_{\rm cool}$ (for $\beta = 0.6$) but the injected power only increases by half an order of magnitude ($f_{\rm cluster}/f_{\rm core} \approx 3...5$).

This is the key result of this paper: Using the best available estimates of the power supplied by radio galaxies into the ICM, we find that it balances (within 1 Mpc) or exceeds (within the core region) the presently existing energy content of the gas including magnetic fields and cosmic rays. An energy input of this order of magnitude is unavoidable and must inevitably be present.

Additional CR energy sources such as supernovae, and shocks from cluster merging events might also form a non-negligible part of the energy budget. We have not attempted any quantitative estimate of the latter two phenomena in this paper. The CR-density produced by supernovae is calculated by Völk, Aharonian & Breitschwerdt (1996) to be 3 - 30 % of the thermal energy content in the Perseus cluster.

4. Consequences for the cluster baryon fraction and cosmology

We have demonstrated that radio galaxies can provide sufficient energy to fill the central intracluster medium with magnetic fields and cosmic ray protons which should be important within the 1 Mpc scale. By analogy to the galactic disk, we surmise that an oversupply will lead to instabilities (Parker 1969) and hence that *an approximate equipartition* between thermal, magnetic and CR-pressure should result. We assume this to be true over a large number of clusters. An additional nonthermal contribution to the pressure could arise from turbulent motion of the ICM, which could result from these instabilities.

The key result of our analysis above is that the X-ray - inferred gas pressure $P_{\rm gas}$ is approximately a factor up to three lower than the real total pressure $P_{\rm total}$. Thus a mass derived by hydrostatics,

$$-\,\frac{dP_{\rm total}}{dr} = \frac{G\,M(r)\,\varrho(r)}{r^2}\,, \tag{19}$$

where $M(r)$ is the mass within a radius of r and $\varrho(r)$ is the gas density derived from X-ray images, without consideration of this nonthermal pressure should be up to a factor three less than the correct mass within the cluster core. The precise factor may vary from cluster to cluster. This would explain the reported mass discrepancy between hydrostatic and lensing mass within the 1 Mpc scale. It requires us to assume that virial mass estimates derived from galaxy motions, which are on average as low as the hydrostatic masses, are likewise often lower by a corresponding factor than the correct masses. The mass fraction of cluster gas $f_{\rm gas} = M_{\rm gas}/M_{\rm tot}$ measured at a few core radii will be obviously strongly affected by this additional pressure.

Even the scatter in $f_{\rm gas} = (0.1...0.3)\,h_{50}^{-3/2}$ derived by hydrostatics (Edge & Stewart, G. C. 1991, David, Jones & Forman 1995, Buote & Canizares 1996), can be interpreted as indicating that the limiting factor

between total and thermal pressures is ~ 3, and that this is reached in a number of clusters. We assume that at least some of this scatter is due to different values of the *additional* pressures in different clusters and expect the true value of $f_{\rm gas}$ to be close to the lower end of the range. In this context it is interesting to note that Squires et al. (1996) , who do not find a mass discrepancy in the outer region of A2218, give a low value $f_{\rm gas} = (0.11 \pm 0.06) h_{50}^{-3/2}$ for this region, which supports our low baryon fraction.

At larger radii hydrostatic gas fractions become less reliable: Since hydrostatic masses are usually derived with the asymptotics of a β-model, they are extremely sensitive to the fitted value of β. But Bartelmann & Steinmetz (1996) show using simulated cluster data that a cut-off radius in the radial X-ray profile resulting from the X-ray background lowers the fitted value of β significantly. If the 'true' β is one, 40 % less thermal gas and energy is within 1.5 Mpc, and the possible range of hydrostatical influence of RG increases. The calculated total mass increases with β as Bartelmann & Steinmetz (1996) note, and therefore the gas fraction is strongly reduced at large scales, even without sufficient nonthermal pressures. Further, a spectroscopically unresolved temperature decrease at large radii (resolved by Markevitch (1996) and Markevitch, Sarazin & Henrikson (1996)) or strong decreasing nonthermal pressures would imply a pressure gradient stronger than that of a β-model fitted with X-ray data. The resulting total mass would be higher and the baryon fraction would be lower than derived with the standard analysis.

$f_{\rm gas} \approx 0.10 h_{50}^{-3/2}$ could be regarded as an upper limit to the baryonic mass fraction $f_{\rm b} = \Omega_{\rm b}/\Omega_o$ since it is not obvious that all the dark matter in the universe is clumpy $f_{\rm gas} \geq f_{\rm b}$. The constraints from nucleosynthesis are $0.04\, h_{50}^{-2} < \Omega_{\rm b} < 0.06\, h_{50}^{-2}$ (Walker et al. 1991) ...$0.09\, h_{50}^{-2}$ (Copi, Schramm, & Turner 1995) which adjusts the clumping part of the matter, which we shall identify with $\Omega_{\rm cold}$, to

$$0.4\, h_{50}^{-1/2} < \Omega_{\rm cold} < 0.6 ... 0.9\, h_{50}^{-1/2}\,. \tag{20}$$

We note that Ω_o will be even higher than $\Omega_{\rm cold}$ if there is an appreciable mass fraction of hot dark matter outside of rich clusters, in the universe. Several recent papers (e.g. D.-W. Kim & Fabbiano 1995; White et al. 1993; Buote & Canizares 1996) have argued that there is a baryon problem in clusters of galaxies, given that the data seem to show that the baryonic mass fraction in clusters was higher than suggested by nucleosynthesis for the entire universe. This baryon problem disappears in our approach, since the relative baryon mass is reduced by a factor of up to 3.

5. Discussion

Starting with an analogy to the galactic disc, where nonthermal pressures exceed the thermal pressure, we have demonstrated that a similar nonthermal pressure component in clusters of galaxies could close the gap between the mass derived from the observed scale hight of the gas distribution and the mass derived from strong lensing, which occurred in a number of clusters. One nonthermal phase would be cluster core magnetic fields on the order of 10μG, directly observed in some clusters with central radio galaxy and cooling flow, and probably typical of all clusters, if the (poorly known) field reversal scale is as small as ~ 0.1 kpc. Another phase consists of cosmic ray protons, that have cooling times equal to or larger than a Hubble-time. The most important source of fields and energetic protons are probably radio galaxies, which are frequently found in clusters. We derive an empirical law connecting the synchrotron emission of the "fast" cooling electrons in the lobes of radio galaxies and their jet power including electron, proton and magnetic power. We integrate the evolution of the radio luminosity function with this law and demonstrate that the injection of nonthermal phases into the central cluster region during the lifetime of a cluster should amount to several times the thermal content of the ICM there. Even within a one Mpc radius the injected energy should be on the average comparable with the thermal content. At larger radii the average accumulated energy should be lower than the thermal energy, unless radio galaxies are more powerful than we assumed or the gas temperature decreases strongly at large radii (Markevitch 1996; Markevitch, Sarazin

& Henrikson 1996). We think it likely that some fraction of the injected jet power is converted through instabilities to turbulent ICM motion.

If this model is, as we propose, the principal solution to the mass discrepancy (in combination with systematic errors at scales above 1 Mpc (e.g. Bartelmann & Steinmetz 1996), a low baryon fraction $f_{\rm b} \approx 0.1\, h_{50}^{-3/2}$ should result , which leads to a high estimate of $\Omega_{\rm cold} \geq 0.4\, h_{50}^{-1/2}$.

This paper was conceived during a small meeting organized by the Chinese Academy of Science and the Max Planck Society at Nandaihe, Hebei, China, in August 1994. PLB would like to acknowledge the generous hospitality of his hosts at Beijing, Tianjin, Nanjing, Hefei and Nandaihe. TAE would like to acknowledge the helpful discussions with Jörg Rachen and Wolfram Krülls.

REFERENCES

Allen, S. W., Fabian, A. C., & Kneib, J. P. 1996, MNRAS, 279, 615

Auriemma, C., Perola, G. C., Ekers, R., Fanti, R., Lari, C., Jaffe, W. J., & Ulrich, H. 1977, A&A, 57, 41

Bahcall, N. A., & Chokshi, A. 1992, ApJ, 385, L33

Bahcall, N. A., & Lubin, L. M. 1994, ApJ, 426, 513,

Bartelmann, M., Steinmetz, M. 1996 MNRAS submitted, astro-ph/9605043

Böhringer, H., Voge, W., Fabian, A. C., Edge, A. C. & Neumann, D.M. 1993 MNRAS, 264, L25

Bell, R. A. 1978, MNRAS, 182, 147

Bell, R. A. 1978, MNRAS, 182, 443

Biermann, P. L., & Strittmatter, P. A. 1987, ApJ, 322, 643

Biviano, A., Girardi, M., Giuricin, G., Mardirossian, F., & Mezzetti, M. 1992, ApJ, 396, 35

Buote, D. A., & Canizares, C. R. 1992, ApJ, 400, 385

Buote, D. A., & Canizares, C. R. 1996, ApJ, 457, 565

Burns, J. O., Rhee, G., Owen, F. N., & Pinkney, J. 1994, ApJ, 423, 94

Carlberg, R. G. 1994a, ApJ, 433, 468

Carlberg, R. G. 1994b, ApJ, 434, L51

Castander, F. J., et al. 1995, Nature, 377, 39

Copi, C. J., Schramm, D. N., & Turner, M. S. 1995, Phys. Rev. Lett., 75, 3981

Dar, A.,& Shaviv, N. J. 1995, Phys. Rev. Lett., 75, 3052

David, L. P., Arnaud, K. A., Forman, W., & Jones, C. 1990, ApJ, 356, 32

David, L. P., Slyz, A., Forman, W., Vrtilek, S. D. 1993, ApJ, 412, 479

David, L. P., Jones, C., & Forman, W. 1995, ApJ, 445, 578

Donea, A. C., & Biermann, P. L. 1996, A&A, in press

Drury, L. O'C., Aharonian, F. A., & Völk, H. J. 1994, A&A, 287, 959

Dunlop, J. S., & Peacock, J. A. 1990, MNRAS, 247, 19

Edge, A. C., Steward, G. C., Fabian, A. C., & Arnaud, K. A. 1990, MNRAS, 245, 559

Edge, A. C., & Stewart, G. C. 1991, MNRAS, 252, 414

Falcke, H., & Biermann, P. L. 1995, A&A, 293, 665

Falcke, H., & Biermann, P. L. 1996, A&A, 308, 321

Falcke, H., Malkan, M. A., & Biermann, P. L. 1995, A&A, 298, 375

Felten, J.E. 1996, *Clusters, Lensing, and the Future of the Universe* ASP Conf. Series Ed: V. Trimble and A. Reisenegger 88, p. 271

Feretti, L., Dallacasa, Giovannini, G., & Tagliani, A. 1995, A&A, 302, 680

Gubanov, A. G., & Dagkesamanskii, R. D. 1988, In A. D. Kuz'min, editor, Clusters of Galaxies and Extragalactic Radio Sources, p. 51. Nova Science Publishers, New York Budapest

Gould, R. J. 1972, Physica, 58, 379

Halzen, F. 1996, to appear in: "Neutrino 96", Helsinki, Finland, astro-ph/9608185

Hayashida, K. et al. 1996, Phys. Rev. Lett., submitted

Henry, J. P., Gioia, I. M., Maccacaro, T., Morris, S. L., Stocke, J. T., & Wolter, A. 1992, ApJ, 386, 408

Jones, C., & Forman, W. 1984, ApJ, 276, 38

Kim, D.-W., & Fabbiano, G. 1995, ApJ, 441, 182

Kim, K.-T., Kronberg, P. P., & Tribble, P. C. 1991, ApJ, 379, 80

Kronberg, P. P. 1994, Rep. Prog. Phys., 57, 325

Laing, R. A., Riley, J. M., & Longair, M. S. 1983, MNRAS, 204, 151

Ledlow, M. J., & Owen, F. N. 1995, AJ, 109, 853

Loeb, A., & Mao, S. 1994, ApJ, 435, L109

Loveday, J., Maddox, S. J., Efstathiou, G., & Peterson, B. A. 1995, ApJ, 442, 457

Markevitch, M. 1996, ApJ, 456, 437, astro-ph/9605026

Markevitch, M., Sarazin C. L., Henriksen, M. J. to appear 1996 in: "X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas", Tokyo, astro-ph/9606113

Merritt, D. & Gebhardt, K. to appear 1996 in: Rencontres de Moriond, "Clusters of Galaxies", F. Durret, editor, astro-ph/9510091

Miley, G. K. 1980, ARA&A, 18, 165

Miralda-Escudé, J., & Babul, A. 1995, ApJ, 449, 18

Owen, F. N. 1975, ApJ, 195, 593

Parker, E. N. 1969, Space Sci. Rev., 9, 651

Petry, D., et al. 1996, A&A, 311, L13

Rachen, J., & Biermann, P. L. 1993, A&A, 273, 161

Rachen, J., Stanev, T., & Biermann, P. L. 1993, A&A, 273, 377

Rawlings, S., & Saunders, R. 1991, Nature, 349, 138

Rephaeli, Y. 1987 MNRAS, 225, 851

Salpeter, E. E. 1984, In G. Setti & L. Van Hove, editors, First ESO-CERN Symposium, p. 180

Sarazin, C. L., Baum, S. A. & O'Dea, C. P. 1995 ApJ 451, 125

Schindler, S., Hattori, M., Neumann, D. M., Böhringer, H. 1996, A&A, submitted

Serna, A., Alimi, J. M., & Scholl, H. 1994, ApJ, 427, 574

Squires, G., Kaiser, N., Babul, A., Fahlman, G., Woods, D., Neumann, D. M., & Böhringer, H. 1996, ApJ, 461, 572

Sreekumar, P. et al. 1996, ApJ, 464, 628

Stanev, T., Biermann, P. L., Lloyd-Evans, J., Rachen, J., & Watson, A. 1995, Phys. Rev. Lett., 75, 3056

Steigman, G., & Felten, J. E. 1995, Space Sci. Rev., 74, 245

Taylor, G. B., & Perley, R. A. 1993, ApJ, 416, 554

Völk, H. J., Aharonian, F. A. & Breitschwerdt, D. 1996, Space Sci. Rev. 75, 279

Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H. 1991, ApJ, 378, 186

Wentzel, D. G. 1974, ARA&A, 12, 71

White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429

Wu, X.-P. 1994, ApJ, 436, L115

Wu, X.-P., Fang, L.-Z. 1996, ApJ, 467, L45

Yeppes, G., Domínguez-Tenreiro, R., & Del Pozo-Sanz, R. 1991, ApJ, 373, 336

Table 1. Expected Gamma-Ray Fluxes

Cluster	F_γ this paper (counts $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	F_γ from Dar & Shaviv (1995) (counts $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	F_γ EGRET upper limits (counts $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)
A426 Perseus	$12 \cdot 10^{-8}$	$10 \cdot 10^{-8}$	$\cdots$
Ophiuchus	$9 \cdot 10^{-8}$	$\cdots$	$\cdots$
A1656 Coma	$6 \cdot 10^{-8}$	$5 \cdot 10^{-8}$	$4 \cdot 10^{-8}$
M87 Virgo	$3 \cdot 10^{-8}$	$22 \cdot 10^{-8}$	$4 \cdot 10^{-8}$

Note. — Expected gamma-ray fluxes above 100 MeV from X-ray luminous clusters. The first column gives the values calculated with equation (10), data from (David et al. 1993) and $\alpha_{\rm CR} = 1$ and the second the values given in (Dar & Shaviv 1995) . The last column gives measured $2\,\sigma$ upper limits ($cl = 95\%$) from EGRET (Sreekumar et al. 1996)